Feasibility Study for a Demonstration Plant for Liquefaction and Coprocessing of Waste Plastics and Tires

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Introduction

For the past several years, a research program on the conversion of waste polymers and coal into oil using direct liquefaction technology has been sponsored by the U.S. Department of Energy. The research has been carried out by a combination of academic, industrial and government scientists and engineers. Most of the laboratory research has been conducted by the Consortium for Fossil Fuel Liquefaction Science (CFFLS), a five university research consortium with participants from the University of Kentucky, Auburn University, the University of Pittsburgh, the University of Utah and West Virginia University. Industrial participation has been provided by Hydrocarbon Technologies, Inc. (HTI), where pilot scale and continuous tests have conducted, Consol, where specialized analytical techniques have been employed, and the Mitre Corporation, where economic analyses have been carried out. The in house research staff at the Federal Energy Technology Center (FETC), Pittsburgh, have conducted a variety of experiments to complement work in the academic and industrial sectors.

The current paper presents a brief summary of a feasibility study for a first demonstration plant for this technology. A complete report of this study [1] should be available by the time of the current meeting. The study was conducted by a committee (see acknowledgement for a list of members) that included participants from the CFFLS, FETC and Burns & Roe. The goals of the study were as follows:

1. To establish a conceptual design for the demonstration plant.
2. To carry out an economic analysis and environmental assessment.
3. To develop a group of stakeholders for the technology.

Potential Resource and Current Practice

Currently, over 44 billion lbs. of waste plastic [2] are disposed of in the U.S. each year. This is approximately 175 lbs. of waste plastics for every man, woman and child in the country. Plastic recycling in the U.S. is primarily mechanical recycling - melting and re-extruding used plastics into recycled plastic components. Uncolored high density polyethylene (HDPE), or milk jugs, is the preferred feedstock for mechanical recycling, although colored HDPE can be used for some types of products, such as plastic lumber, park benches, and marine pilings. Polyethylene terephthalate (PET), used primarily for soft drink bottles, can be recycled into synthetic fibers and carpet feedstock. According to the EPA, [3] approximately 50% of PET soft drink bottles and 30% of HDPE milk and water bottles are recycled but only about 5% of all waste plastics.

Over 280 million automotive tires [4] are disposed of annually in the U.S., or approximately one tire (~20 lbs.) for each person. Furthermore, it is estimated that there are 4 billion tires "on the ground" in this country. Tires are combusted, usually with coal, in utility boilers to produce electricity [5] and they are burned in cement kilns; although these methods of utilizing waste tires are productive, they are not recycling. As part of this study, visits were made to a tire shredding and recycling company. [6] Most of the tires are shredded to a nominal size of 2-4 inches and sold to utilities for combustion. The tipping fee of $0.75 - $1.00 per tire approximately pays the cost of shredding. The price paid by utilities for shredded tires is $20 –25 per ton. At a size of 2-4 inches, most of the steel wire is retained in the tires and it is incorporated into the slag or ash.

A smaller percentage of used tires is shredded to small particle sizes, either by means of recycling through the shredder with finer screen sizes or using such methods as cryogenic comminution, which produces a product known as crumb rubber. [6] Steel wire is separated in the process by magnetic and other methods and can be sold as scrap steel. Crumb rubber is used as an additive to asphalt [7] and for fabrication of rubber mats used for playgrounds, running tracks, stables, etc. A small percentage of crumb rubber (5-10%) from used tires can be added back into new tires; automobile manufacturers may require this in the near future. The cost of producing crumb rubber is approximately 10-20¢ per pound and it is normally sold for 40-50¢ per pound. [6] Currently, 15% of the tires disposed of in this country are recycled. [3]

Waste oils, greases and fuels are also considered in the current report. Although they are not polymers, they are petroleum-derived and coprocess with waste plastics and rubber extremely well. Currently, approximately 30 million barrels of waste lubricating oil, grease and fuel must be either reprocessed or disposed of in the U.S. each year. [8]

The quantities of oil and valuable by-products that could be recovered by liquefaction and upgrading the waste polymers generated annually in the U.S. are estimated in Table 1, assuming a yield of 5 barrels of oil per ton of hydrocarbon feedstock. Important byproducts include carbon black and steel wire from the tires, and aluminum foil derived from labels and lids on plastic containers.

Table 1. Quantities and value of potential products from waste polymers

Waste polymer	Tons/year	Oil (barrels/yr)	By-product (tons/yr)	Value ($/yr)
Plastics	22 million	110 million	Al foil (220,000)	44,000,000
Tires	2.8 million	8.4 million	Carbon black (840,000)	168,000,000
			Steel wire (280,000)	14,000,000
Waste oil		30 million		
Total Oil		148 million		2,960,000,000
Total Potential Revenue				**$3,186,000,000**

In arriving at the dollar values of the products in Table 1, rather conservative values have been assumed: oil - $20/barrel; activated carbon black - $200/ton; aluminum - $200/ton; and steel - $50/ton. It is assumed that the carbon black has been activated and cleaned. In addition to the loss of this potential revenue, approximately a billion dollars per year is currently being spent to put most of these waste materials into landfills. Furthermore, coprocessing these wastes with coal and petroleum resid could approximately double the potential oil resource.

<u>German feedstock recycling industry</u>

The country with the most aggressive recycling program in the world is undoubtedly Germany. The development of the German recycling industry has been in response to very restrictive legislation that requires 80% of all consumer packaging materials to be recovered and 80% of all materials recovered to be recycled. The response of German industry to this law has been the creation of the Duales System Deutschland or DSD. Member companies of the DSD place a small surcharge (roughly a penny) on every container they sell. The money collected (~4 billion DM) is used to subsidize companies that collect, separate, prepare and recycle waste packaging material. DSD supports processing plants that convert the waste plastic into oil, olefins, synthesis gas, and reducing gases for production of steel in blast furnaces. The processing plant closest to the technology discussed in the current report is the liquefaction plant of Koheöl-Anlage Bottrop, GmbH (KAB), which is currently liquefying 80,000 tons of DSD waste plastic feedstock per year. As part of the feasibility study, members of the committee had many valuable interactions with representatives of the DSD and their contractors and a complete description of their operations is given in the full feasibility study report. [1]

<u>Research Summary</u>

Recent research in the U.S. has been summarized in several conference proceedings volumes. [9-11] Much research and development has also taken place in Germany. [12-16] Some of the results that are most pertinent for demonstration plant development are given below.

<u>Plastic liquefaction and coprocessing:</u> The liquefaction of commingled waste plastic typically yields 80-90% oil, 5-10% gas, and 5-10% solid residue. Solid acid catalysts and metal-promoted solid acid catalysts improve oil yields and oil quality. At temperatures above 440 °C, thermal and catalytic oil yields are comparable but lighter oil products are produced catalytically. No solvent is required but good results have been with mixtures of waste oil and plastic. The reactions can be carried out at low hydrogen pressures (~100-200 psig) and with low hydrogen consumption (~1%).

Coprocessing of plastic with coal and resid has been investigated. Generally, the best results have been obtained when using catalysts with both hydrogenation and hydrocracking functions, such as metal-promoted SiO_2-Al_2O_3 or mixtures of metal hydrogenation catalysts with HZSM-5.

Oil yields of 60-70% and total conversions of 80-90% have been obtained. High hydrogen pressures and a solvent with some aromatic character such as petroleum resid are required.

Rubber liquefaction: Crumb rubber is readily liquefied at 400 °C under low hydrogen pressures (~100-200 psig), yielding 50-60% oil, 5-10% gas, and 30-40% carbon black. The oil product is improved by the presence of a metal hydrogenation catalyst such as nanoscale iron or molybdenum sulfide. Experiments on the coprocessing of tire rubber with coal indicate that rubber converts to oil in the same manner as it does when coal is not present. High hydrogen pressures and a hydrogenation catalysts are required for coprocessing of rubber and coal. Because of their relatively high content of carbon black (~30%) and wire (~10%), the feasibility committee concluded that the best approach for tires is to pyrolyse them and hydrotreat the pyrolysis oil, either alone or in mixtures with coal and/or plastic. The carbon black and wire can then be easily separated as byproducts of the process. Activation of the carbon black yields a carbon product with a surface area of several hundred m^2/g.

Plant Design

A modular design was chosen for the demonstration plant. The three principal modules for the base design, illustrated in Figure 1, are as follows:

(1) Tire module - tire pyrolysis, separation of steel wire, and activation/upgrading of carbon black.

(2) Waste plastic module - Melting/depolymerization (M/D) of plastics at a moderate temperature (~380 °C), condensation of light volatile oils with removal of volatile HCl, removal of Al foil and other inerts, and hydrocracking of the liquid product.

(3) Upgrading module - catalytic upgrading of the liquid products from modules 1 and 2 in a slurry phase reactor using a dispersed, nanoscale, iron-based catalyst and distillation of the upgraded product.

An alternative for the waste plastic module is to replace the M/D reactor with a pyrolysis reactor. Such reactors operate at temperatures of 500-750 °C, depending on the type of reactor and residence time, and typically produce about half as much liquid product and two to four times as much gas and solid residue. However, the capital investment is smaller.

A modular approach was adopted to allow potential developers to choose the modules that best suit their needs. For example, if tire recycling is the main objective, modules 1 and 3 would be needed. If converting plastics into high quality oil is the goal, modules 2 and 3 are required. However, module 2 alone would produce a good oil product that could meet the requirements of some developers.

Other feedstocks considered are pyrolysis oils and tars from coal, petroleum resid, and waste oil. It is assumed that these feedstocks require no preparation module, other than possibly heating to lower the viscosity to allow easy feeding to the upgrading module.

Economic analysis: Independent economic analyses for the plant were carried out by Harvey Schindler of Burns & Roe Services Corp. and by Mahmoud El-Halwagi and Mark Shelley of the CFFLS and Auburn University. The uncertainty in the results of the economic analysis is considered to be fairly large (± 30%) for the following reasons:

(1) The small size of the plant (200 tons/day of plastics and 100 tons/day of tires) necessitated scaling down the cost of much larger units.
(2) There were wide variations in equipment cost quotes from different manufacturers.
(3) The committee identified several unanswered research questions related to plant design.

Several modular combinations are considered in the economic analysis given in the complete feasibility report. [1] In the current paper, however, in the interest of space, only the base design shown in Figure 1 will be discussed. The results are summarized in Tables 2-4 and Figure 2. In Tables 2 and 3, Schindler's results are given in column 2 and El-Halwagi's and Shelley's appear in column 3. The costs are given in units of millions of dollars ($MM). It is seen that some of the capital and operating costs in columns 2 and 3 are in reasonable agreement, while others differ significantly. The differences reflect markedly different equipment cost quotations received from different vendors and differences of opinion on the operating requirements of different units in the plant. Currently, the committee is still working to resolve these differences. For the current paper, the author has assumed a set of capital and operating costs arrived at after discussions with Schindler, El-Halwagi and Shelley that appear to be a reasonable compromise. These costs appear in column 4 of Tables 2 and 3. Table 4 gives the product values, total revenues, profits and returns on investment (ROI) for the plant using the compromise costs. The results in Table 4 are arrived at assuming plant operation for 330 days per year with the product values and tipping fees indicated in column 1. Four different scenarios are considered for waste tires. Case A is the most conservative; it assumes that the shredded tires are purchased from a tire recycling company at a cost of $20/ton. Cases B assumes that shredded tires are delivered to the plant free, while case C assumes that shredded tires are delivered to the plant and the supplier pays the plant a tipping fee of $20/ton. These cases are based on discussions with environmental officials from two states who indicate that they are now paying to have waste tires shredded and then paying to have the shredded tires placed in landfills. Finally, case D assumes that whole tires are delivered to the plant with a tipping fee of $0.75/tire and are shredded at the plant.

The results are quite promising. With a tipping fee of $30/ton for waste plastics, the ROI ranges from 8.6% to 13.5% for cases A to D at an oil price of $20/barrel and from 12.7% to 17.6% at an oil price of $25/barrel. For a 15 % ROI at $20/barrel, the required tipping fee per ton of waste plastic ranges from $41 to $78/ton. Anticipating that tipping fees will continue to rise in this country as they have in the rest of the world, the ROI has been calculated as a function of the tipping fee for waste plastics and the results are shown in Figure 2. Here, the four solid lines are the results for $20/barrel oil and the four dashed lines are the results for $25/barrel oil assuming the four scenarios discussed above for tire tipping fees. It is seen that ROIs of 15-25% are not unreasonable for this demonstration plant.

Conclusions

A brief summary has been given of some of the results of a feasibility study for a demonstration plant for the liquefaction of waste plastics and tires and the coprocessing of these solid wastes with coal, resid and waste oil. The current paper considers the economics only for liquefaction of plastics and tires. The results for a 300 ton/day (200 - plastics, 100 - tires) demonstration plant are quite promising. With oil priced at $20/barrel, the ROI on a capital investment of $49.7 million is estimated to range from 8.6 % to over 20 %, depending on the tipping fees received for waste plastics and tires. With oil priced at $25/barrel, the ROI ranges from 12.7 % to over 25 %. These results are considered particularly encouraging in view of the fact that significant economies of scale could be realized with larger plants. Thus, it seems quite possible that a successful demonstration plant of the size envisioned could lead to a new industry that converts waste polymers into oil and other valuable byproducts.

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Table 2. Capital costs - case 1: tire pyrolysis, plastics M/D, and upgrading modules.

Unit	Schindler, $MM	Auburn, $MM	Compromise, $MM
Tire pyrolysis	4.300	4.500	4.400
Plastics shredding	10.000	0.339	3.500
Plastics M/D	7.000	9.000	8.000
Plastics hydrocracker	2.910	11.41	7.16
Hydrogenation reactor	4.703	8.55	4.703
Carbon black activation	2.000	2.000	2.000
Hydrogen purification	1.698	0.085	0.085
Product fractionater	0.826	0.594	0.710
General offsites	11.032	11.006	11.019
Subtotal	44.469	47.484	41.417
Contingency(20%)	8.894	9.497	8.315
Total	53.363	56.981	49.732
Capital recovery (15%)	8.004	8.547	7.460

Table 3. Operating costs - case 1: tire pyrolysis, plastics M/D, and upgrading modules.

Cost Item	Schindler, $MM	Auburn, $MM	Compromise, $MM
Maintenance	1.512	2.432	1.678
Labor	3.160	1.920	2.54
Utilities	0.771	1.015	0.893
Purchased hydrogen	0.823	0.774	0.799
Catalysts	0.628	0.338	0.483
Lime	0.327	0.074	0.201
Other chemicals	0.077	0.088	0.083
Solid waste disposal	0.026	0.702	0.297
Wastewater treatment	0	0.009	0.009
Total	**7.984**	**8.012**	**7.643**

Table 4. Product values, profit and ROI for Compromise costs in Tables 2 and 3. Plant is assumed to operate 330 days per year.

Product	$MM[(A)]	$MM[(B)]	$MM[(C)]	$MM[(D)]
Oil at $20/bl	8.296	8.296	8.296	8.296
Act. carbon black - $200/ton	1.795	1.795	1.795	1.795
Steel - $50/ton	0.238	0.238	0.238	0.238
Aluminum - $200/ton	0.264	0.264	0.264	0.264
Plastic tipping fee - $30/ton	1.980	1.980	1.980	1.980
[(A)]Shredded tires cost $20/ton	-0.660			
[(B)]Shredded tires are free		0		
[(C)]Shredded tires bring tipping fee of $20/ton			0.660	
[(D)]Tires shredded at plant; tipping fee of $0.75/tire.*				2.475
Total Revenue with oil at $20/barrel	**11.913**	**12.573**	**13.233**	**15.048**
Profit	4.270	4.930	5.590	6.845
ROI with $30/ton tipping fee for plastics	8.59 %	9.91 %	11.24 %	13.50 %
Plastic tipping fee for 15% ROI	$78/ton	$68/ton	$58/ton	$41/ton
Total Revenue with oil at $25/barrel	**13.976**	**14.636**	**15.296**	**17.111**
Profit	6.333	6.933	7.653	8.808
ROI with $30/ton tipping fee for plastics	12.73 %	14.06 %	15.39 %	17.62 %

*For case D, in which the tires are shredded at the demonstration plant, there is an increase in total capital costs of $248,000 and an increase in annual operating costs of $660,000.

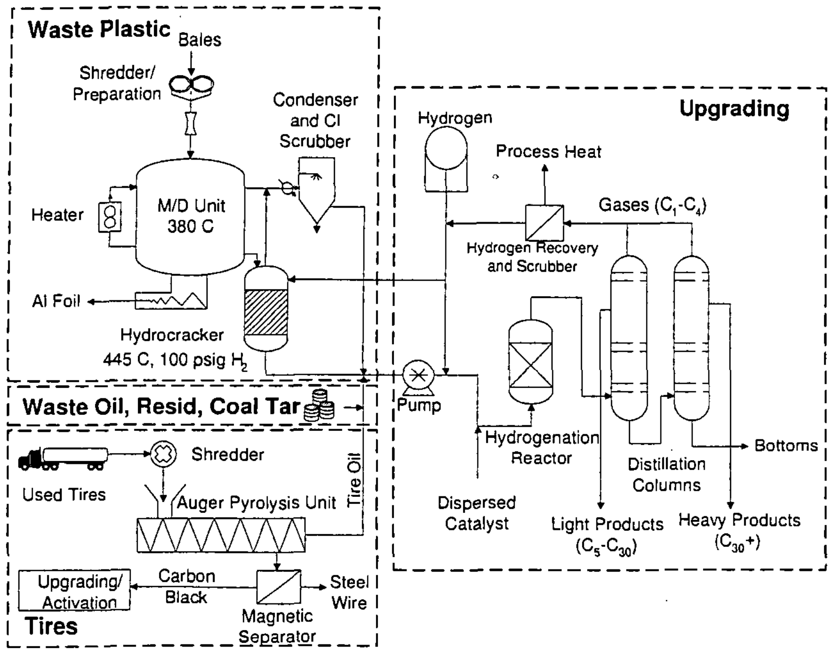

Figure 1. Conceptual design for a demonstration plant for liquefaction and co-processing of waste plastics and tires.

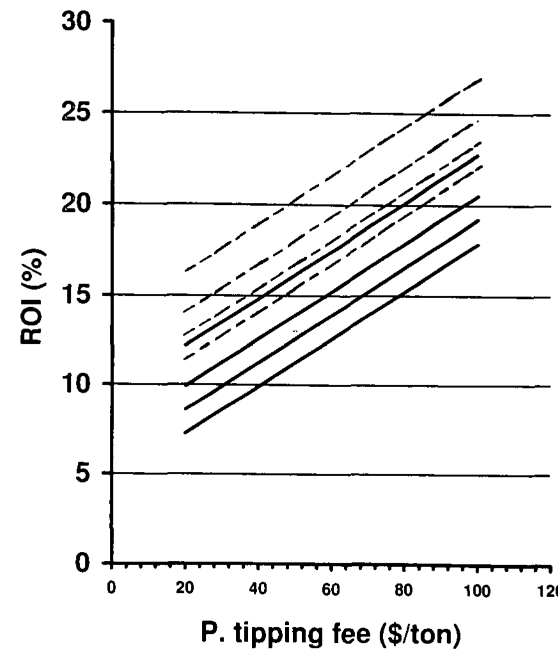

Figure 2. ROI vs. plastic tipping fee.